The Open University

Appropriate Technology Group

Second Wave Energy Seminar 1984

Report of the Second Wave Energy Seminar - 1984

Organised by Michael Flood of the Alternative Technology Group and held at the Open University, 13th July 1984.

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17.4.85.

Contents

1. Introduction

The 1984 Wave Energy Seminar was held as a meeting place for practitioners in wave energy research and development. A strong feeling had emerged from the 1983 Wave Energy Seminar that a greater emphasis should be placed on technical discussion since this was one of the few forums available exclusively devoted to wave energy.

Most of the day was taken up by presentations by each of the teams actively involved in wave energy R & D, and presentations were also made by colleagues from Norway and Eire. A wide ranging discussion on the political context and future developments in wave energy rounded off the day, but since this discussion was "off the record", only the most general of outlines is included here.

I would like to take the opportunity on behalf of all participants, to thank Mike Flood and the Alternative Technology Group at the Open University for organising what proved to be a most useful seminar.

Garry Jenkins

2. Work in progress: reports from device teams

2.1 NEL Oscillating Water Column

NEL and a consortium of companies* have been investigating building a small bottom-standing Oscillating Water Column off the Isle of Lewis in the Outer Hebrides since May 1983. It would be operated by the North of Scotland Hydro Electric Board.

* The consortium included: Sir R. McAlpine, Roxburgh and Partners, and Herrema who were studying civil engineering aspects; Sulzer U.K. who was investigating the turbine; and NEI Ltd. who were studying electrical generation and transmission.

The prototype was 88 metres long designed to stand in 14 metres of water. It contained three separate columns and had an installed capacity of 5MW. Estimated costs were put at around £15 million. The consortium was 33% funded by the Department of Industry. NEL had been involved with the development of a novel bidirectional turbine the 'Reflair', which is similar in concept to the Wells turbine. A 1/4 scale model of the device (0.6m diameter) was undergoing extensive testing in the laboratory. This work was described.

The consortium was actively looking at a variety of design options for wave energy conversion and not just for the UK, but also for an unspecified overseas government. These included designs for a 5MW device for use by isolated communities and a 25MW scheme which could be integrated into a harbour wall. It was suggested that, if built, the Lewis device could provide a 'shop window' for overseas governments interested in developing their wave energy resources.

The economics of the prototype intended for the North of Scotland Hydro-Electric Board's 24MW Lewis Island grid were discussed. The financial assessment suggested overall costs of less than 5p/kWh. It assumed an average annual wave energy input of around 30kW/m; a duty factor of 55%; a 60 year structural life; and M & E plant replacement at 30 years. The discounting system was identical to that used by the Department of Energy only the rate had been increased to 6%. The installation would be for a <u>real</u> power station in the NoSHEB system. It would be handed over to NoSHEB after 9 months commissioning and would be used to reduce diesel consumption. A decision to go ahead, if it were taken, would be based solely on economic criteria, and most importantly, the cost of oil. A prime site with specific high energy features had been selected, and much work had already been carried out on system optimisation. It was envisaged that the prototype would be built on a rented barge, with maintenance facilities based at an existing harbour.

The overall concept appeared attractive enough for the partners to move on to the next stage of work, a 12-18 month detailed design study for Lewis. If this were to be successfully completed, concrete pouring could begin in 18 months (autumn 1985) and should take 12 months.

2.2 Belfast Buoy device (see Appendix A)

The initial discussion concerned the development by the team at Queen's University, Belfast, of a prototype single chamber, omni-directional device. It was noted that problems had been encountered in connecting the lower balancing mass to the chamber superstructure. More recent development work had concentrated on a bottom-mounted device with 9 separate chambers, 6 at the bottom of the device and 3 higher up, each chamber having a separate Wells turbine and generator.

Another project involved the monitoring by line-of-sight telementry, of an Irish Lights navigation buoy with a small Wells turbine generator. The navigation light had not been linked to the system but this was planned. Data collection had proved difficult because of interference.

Irish lights now have 30-40 Japanese short tube buoys in operation.

An experimental high-solidity (0.6) Wells turbine was illustrated. After 6 months operation in a marine environment there had been no noticeable corrosion of the aluminium blades. Tip speeds were in the range 140-160m/s. It was pointed out that the design of turbine is very dependent on the duty required. The configuration of the Queen's University turbine was very different from that of the SEA Clam, even when similar power ratings were considered.

2.3 The Clam device

SEA Energy Associates and Lanchester Polytechnic had been working on a 270m long, 10MW rated version of their Clam device, consisting of 10 bags each with a separate 1MW, 3.5m diameter Wells turbine. It was reported that tests at 1/50th - scale in the Cadnam wave tank had highlighted problems with scaling the air power take off system. These had been investigated further in a 1/11th - scale model tests in Loch Ness. The device was equipped with 10 bags. It was 27m long, and weighed a total of 20 tonnes. Results from these trials bore out the results of the Cadnam tests.

Provisional estimates have suggested that large scale Clam wave energy converters (built to the Government's 2GW Reference Design) should deliver electricity at around 5p/kWh.

The device team had recently switched its attention to smaller devices with the aim of developing a commercial system with a rating of around 600 kW. A 1/11th scale model of such a device had been undergoing tests in Loch Ness. It was 6m long and had 8 bags which each moved air through a Wells turbine simulator into a common chamber. The model is designed so that a number of critical parameters can be varied including the length and the depth of the device and the damping of the turbine simulators. These tests, to determine the optimum size of device, have confirmed productivity calculations (made in 1983) and have improved confidence in the strength of bag materials and in viscosity effects. The overall efficiency (air power captured/wave power available) was around 50%, which was better than the previous, longer version.

Two simulation programmes were reported to be in hand. The first involved the complete power train and was directed towards determining the 'shape and quality' of the power output, as well as the power output efficiency obtained from the Loch Ness trials.

A second simulation was being carried out in conjunction with SERC, and concerned studies of the hydrodynamic interaction between bags and sea. This was being studied for a number of different turbine designs.

The civil and M & E design of the 600kW Clam was under way, and had so far suggested costs similar to initial predictions although these were not disclosed. This suggested that much smaller devices could be economical in South Uist seas.

It was pointed out that a new philosophy was emerging among the wave energy teams and that this was concerned with minimising the cost of power output. This was markedly different from the Department of Energy's philosophy which had been to maximise the quantity of power landed. Devices were now being developed which were intended for specific wave climates and 'tailored' to suit customers' needs.

The session closed with a brief discussion about the scaling up of Loch Ness results to other wave regimes.

2.4 Edinburgh Wave Power Project

A number of areas were being covered:

2.4.1 Narrow Tank Testing

Computer simulations had shown that, in larger seas, it was possible to extract more power from the 'mountings' than from the nodding of the Duck. Testing in the narrow tank, on a rig with 7 variables, was aimed at confirming these results and maximising the power obtained from the mountings.

2.4.2 Wide Tank testing

A number of illustrations were given of spine testing in the Edinburgh wide tank. The computer controlled spine was described as a 'Python with controlled rigor mortis'. Details of spine elements, joints and clamping were shown, along with slides of the spine in the tank and the mooring system.

The behaviour of the spine in the 46 standard S. Uist sea states was illustrated, along with a representation of the bending moments experienced by spines of different lengths, stiffness, etc. It has been found that, in general, horizontal bending moments in the spine are about twice the vertical bending moment.

2.4.3. Gyroscopes

A 1/3rd - scale model of a Duck gyroscope has been built by Laing's at Borehamwood and this was shown. The laminated flywheel has now been spun up to speed at the factory in Glasgow and has performed satisfactorily. Indeed, bearing loses have turned out to be lower than was predicted in 1979, and are expected to amount to only 3-4kW. It was noted that the Northern Ireland Electricity Board is planning to use flywheels for large scale energy storage at one of its power stations.

2.4.4 Axial piston hydraulic motors

A half-scale axial piston hydraulic motor has been built with a rating of 600kW. Very high efficiencies were reported -- better than electric motors of similar size -- and these remain relatively constant over a very large power range. (Losses of approximately 1.5% were reported). Such motors could be used to get a synchronous output from a variable sea. Talks were in hand with Kvaerner (Norway) about using this system on the turbine shaft of their planned multiresonant OWC.

2.4.5 Availability

Further studies on availability have been made at both Edinburgh and ETSU and these suggest that overall availability of the Duck system could be over 90%. Unit cost of 3.8 p/kWh were quoted for a device with 100% availability.

2.5 Lancaster University Project (see Appendix C)

A small theoretical and experimental programme, was being carried out on the FROG device with the help of a £16,000 grant. This device was derived from Budal and Falnes work (see Appendix B2), and consisted of a spring and damped sliding mass contained within a floating buoy. The buoy would be 'tuned' to the waveband width to act as an ideal point absorber. An experimental model has been built complete with a latching mechanism. At full scale, the buoy would be expected to weigh 3000 tonnes, and the sliding mass develop around 4000 tonne metres. Points discussed included the shape of the buoy, its size and the problem of 'end stops'. The power take off mechanism was not revealed.

2.6 Norwegian Wave Power Projects

Notes on these projects were circulated at the meeting and are included here as Appendix B.

2.6.1 Latched Power Buoy - University of Trondheim

Illustrations of the current 1/10th scale model were shown.

1984 Status notes - item B1
October 1983 Status Report by Budal and Falnes - item B2

2.6.2 'Multiresonant OWC' - Kvaerner Engineering

An artists impression of Kvaerner's device was shown. (1984 Status notes - item B3)

A prototype is to be built at a site 40km NW of Bergen; map of location item B4. Construction to begin in August 1984.

2.6.3 'Tapchan' Wave Power Device - Norwave

1984 Status notes - item B5. Map of scheme - item B6.
This device utilises a natural tapered channel, which has been enhanced by blasting. Incoming waves will overtop a dam into a basin and discharge through a 350kW Kaplan turbine. The main provided 3-4 minutes of storage, prototype construction was planned to begin at the site shown in item B4 in August 1984.

The 'Norwave' consortium is funded 50% by the Norwegian Department of Energy and 50% by industry.

It was observed that all the Norwegian Department of Energy's funding was directed towards prototype building. No money was available for fundamental research. This was attributed to the 'knock-on' effect that the ending of the UK Wave Energy Programme has had on attitudes in the Norwegian funding agencies.

Editor's Note: A recent article describing the Norwegian work has been included on Appendix E.

2.7 Japanese Wave Power Projects

Masuda's team had recently (November 83) commissioned a small wave energy device which was built in a natural cleft in a cliff and at the end of a 40m long tapered channel. The device was described as a side opening OWC and it was being used as a test-bed for a 40kW Wells turbine. It had a steel subframe and was clad in concrete. It had cost £200,000 and been connected into the grid.

Several slides were shown including the installation of the device and its operation in an 'active' sea.

2.8 Irish Wave Power Project - University of Cork

An ill-fated wave power experiment at Bull Rock was next to be described. Bull Rock lies off Ireland's coast at its most south westerly point. It houses a lighthouse and a colony of birds but little else.

A natural crevis in the rock was causing sea spray which was giving rise to corrosion problems with equipment belonging to Irish Lights. They had planned to block off the crevis completely but were persuaded to leave two holes in their concreting to which orifice plates and logging equipment could be fixed for wave power experiments. (The concreting took 2 men 8-9 months to construct.) The holes each 0.35m in diameter were 17m above sea level, and were completed in 1983. But the experiments were not a success. The equipment broke down in September 1983, and in October a violent storm (significant wave height, 12-14m) blew the concrete plug clean out. The plug was 2m x 1m x 0.5m thick, and had been fixed in position with steel bolts 3/4" thick. Further experiments were planned for the autumn (1984) at a second cleft in the rock which was due to be plugged.

2.9 Wave powered ships - University of Reading

Recent work on wave-powered ships (reported in 'The Motorship' August 1983) was described. Jacobsen had tested a 7.5m hull, which had reached 6 knots under wave power. The mode of operation of wave powered ships was explained by analogy to a sailplane. A 'wing' below the ship is positioned to give rise to a forward component of 'lift' in rising water and repositioned to give a forward component from 'negative lift' in falling water.

It was pointed out that the concept of using wave power to propel ships is not new. It was first suggested in 1894.

2.10 Review of other overseas Wave Power Projects

2.10.1 Mauritius - see Appendix D

2.10.2 France

An overtopping scheme was being developed by E N.S.M. at Nantes for Tahiti and other islands. This tapered channel scheme would use natural features of lagoons to reduce costs. A IMW device, capable of producing around 76Wh of energy per annum, is expected to cost 42 million French Francs. (less than 5p/kWh). A further 'Camembert' device with a 3 point mooring and 'intelligent winches' was also under study.

2.10.3 Sweden

Swedyards were trying to raise money for a prototype heaving buoy device. The patents have been sold to Atlas Copco.

2.10.4 India

A bottom standing OWC was being considered by a group in Madras. It would stand in 10m of water.

2.10.5 Number of workers involved in wavepower overseas (estimates)

Norway	10
Japan	7
India	6
France	5
Ireland	2½
China	2 or 3
Australia	2
Sweden	2
Portugal	4
USA	1
Brazil	?

3. Basic Research in the UK

The list of basic research topics drawn up at the 1983 Wave Energy Seminar was discussed (see below). Some work has been done on the following topics.

3.1 Latching

A small project on latching was being carried out at Reading University.

3.2 Harbour Resonances

The CEGB had conducted experiments on a 1m long bottom mounted OWC with 'harbour walls' to check the relationship between wall size,

wave conditions and power output. The tests had been conducted in open sea off Cowshore Beach. Results obtained, along with theoretical predictions and tests in the Cadnam tank, indicate that harbour walls do work. Factors of improvement in pneumatic power output in the range 1.5 to 2 were reported. In addition harbour walls on a round spine model have substantially reduced the horizontal bending moment experienced in tank tests.

3.3 A Time domain approach had been the subject of a 1 year research programme at University College, London. Realistic OWC models had been used.

3.4 Further topics for basic research

It was thought that research into arrays, with 'intelligent' communication between members of the array would be a fruitful topic of research, and should be added to the list. Further studies of wave climate, especially of "hot and cold spots" and bottom friction were needed.

Basic Research   A possible future programme.

1. Development of a general optimisation procedure or package with well defined objectives and parameters.
2. Parameter sensitivity study.
3. The ultimate device - curves of best possible performance under well-defined constraints.
4. Scale sensitivity study - size and scale/cost relation.
5. Latching in random directional seas.
6. Harbour resonances.

7. Further emphasis on theoretical estimates of sea efficiencies.

8. Further effort on optimisation of spacing between <u>specific</u> devices.

9. Degradation due to non-linear dynamics.

10. Wave climate studies - where <u>does</u> the energy go in shallower water?

11. Time-domain approach to realistic OWC models.

4. <u>The Political Context and Future Developments</u>

General topics discussed were:

The wave energy community's response to ETSU's, R13 and R14 reports and the forthcoming Department of Energy report;

The forming of a 'Wave Energy Association' along the lines of the British Wind Energy Association.

The role of British Renewable Energy Foram (BREF) and the need for a positive response from the wave energy community.

The funding of wave energy R & D in the UK, particularly sources of funds available for the building and testing of prototypes; (eg: Department of Energy, Department of Trade and Industry, SERC, industry, EEC, etc.) and the criteria used by each funding agency;

The response of other countries (especially Norway, Japan) to the Department of Energy closing down most of Britain's Wave Power programme.

The role of competition and collaboration within the UK wave energy community, given the increasingly commercial nature of developments;

The role of competition and collaboration on an international basis, with particular reference to R & D on 'second generation' devices;

The development of international standards for equipment.

The presentation of wave energy to the media and the general public; and finally,

The holding of further Wave Energy Seminars. It was agreed that a further seminar at the Open University in 1985 would be welcomed.

List of Participants

1.	A. Walton Bott	Consultant
2.	Robin Bracewell	Lancaster University
3.	Dr. Brian Count	CEGB Marchwood
4.	John P. Davis	University of Bristol
5.	George Elliot	National Engineering Laboratory
6.	Dr. David Evans	University of Bristol
7.	Johannes Falnes	University of Trondheim, Norway
8.	Professor Francis Farley	University of Reading
9.	Professor Michael French	University of Lancaster
10.	Steve Goddard	Vickers Ltd.
11.	Gordon Goodwin	Department of Energy
12.	Clive Grove Palmer	British Renewable Energy Forum
13.	Rick Jefferies	University College, London
14.	Chris Klewe	CEGB Marchwood
15.	Tony Lewis	University of Cork, Eire
16.	Ken Major	E.T.S.U.
17.	Dr. David McIllhagger	Queens University of Belfast
18.	Dr. Denis Mollison	Heriot Watt University
19.	Chris Retzler	Edinburgh University
20.	David Ross	Press
21.	Stephen Salter	Edinburgh University
22.	Mike Urwin	Wavepower Ltd.,
23.	Dr. Peter White	Lanchester Polytechnic

Chair:	Dr. Michael Flood	Open University
Rapporteur:	Garry Jenkins	Sunderland Polytechnic

APPENDIX A

WAVE POWER RESEARCH AT THE QUEEN'S UNIVERSITY OF BELFAST

Since 1980, part of the QUB research team in conjunction with Trinity House and Irish Lights has been developing and testing wave powered navigation buoys with Wells turbines coupled to electrical generators. During the first stage of the research and development programme a demonstration prototype Wells turbine-generator was designed and constructed for Trinity House. The unit was tested both in the laboratory and on a class 1 buoy moored at the Cork Hole test site off Harwich.

A second research and development stage commenced during 1982, as a consequence of the encouraging results of the initial tests. As the mechanical and aerodynamic design of the turbine-generator is only one part of the development process, it is necessary to assess its long-term reliability and operation in a marine environment for prolonged periods. The primary aim was to test up to ten pre-production units at sea and have a commercial product available by 1985. Queen's University entered into a licence agreement with Ryokuseisha of Japan in 1980 to manufacture Wells trubines for Navigation aids and later completed a licence agreement with Munster Simms Engineering Ltd, NI, to further the second development.

During 1983 two turbine units were manufactured by Munster Simms using design data from Queen's University and a specification of requirements from Trinity House. One replaced the original QUB turbine on the bouy at the Cork Hole test site while the second was installed on a buoy supplied by Irish Lights moored in Belfast Lough, at a new test site developed by Queen's University.

The Irish Lights wave powered buoy and the 100-W Wells turbine generator installed in Belfast Lough are shown in Fig 1. A downward

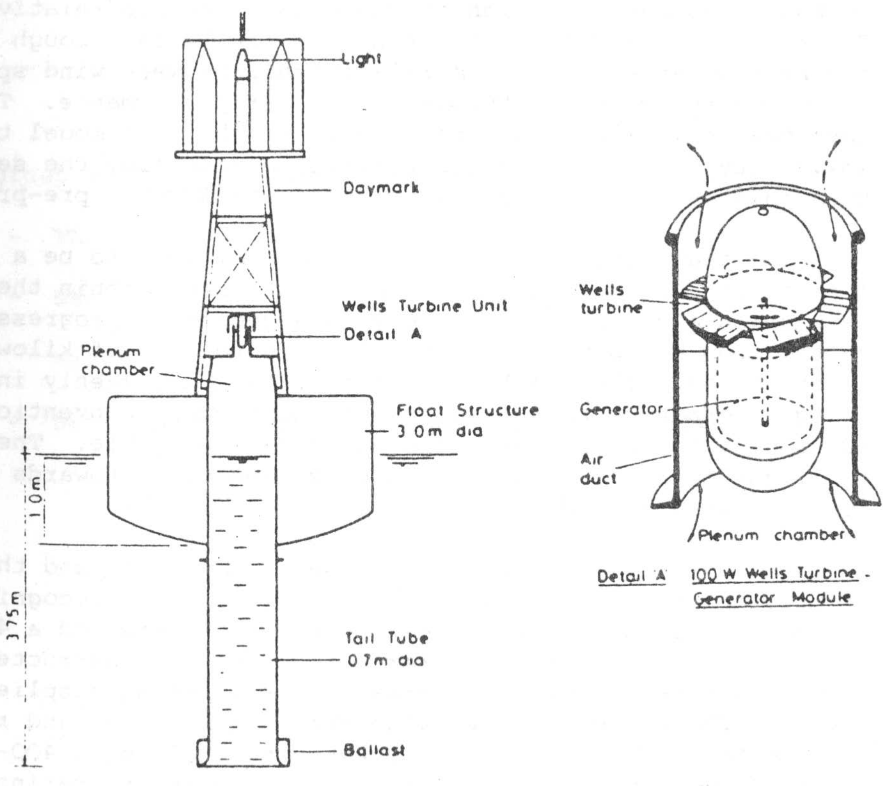

Fig. 1. Irish Lights Tail-Tube Buoy

facing water column is contained within a central cylindrical tail tube, as in the original buoy conceived by Wells. The relative vertical displacements of the buoy and the water column force air from the plenum chamber past the turbine mounted on top of the tube. The electrical output from the generator, direct coupled to the turbine, is passed through a control circuit to the battery storage. The control circuit is necessary to prevent damage occurring to the battery as a result of overcharging. The battery in turn supplies power to the electrical equipment on the buoy.

Queen's University designed and installed the electronic control and data acquisition systems. A radio telemetry link has been established between the University and the buoy - 15 miles away. Information from sixteen channels is transmitted in serial form. The received signal is converted to RS 232 format and stored on hard disk in a Digital PDP 11/23 computer.

Apart from monitoring various voltages and currents throughout the control circuit, measurements are taken of water column displacement, pressure drop across the turbine and rotational speed. Although the wave climate is not being measured, wind data for the area, measured every hour, is obtained from the Met. Office.

An extensive range of software has been written to analyse the data. The data is initially checked for parity errors and it is then sorted before the channel identification numbers are stripped. The reduced data file is then ready for analysis and plotting. Each channel can be analysed in both the time and frequency domains and the data plotted.

No mechanical or electrical problems have occurred in the two prototype machines during the first year of operation at sea. Corrosion on the machines and water ingress to the generators have been adequately prevented. The power requirement of the standard lantern on this type of buoy has been met even though both sites are relatively sheltered. The extensive bank of data taken from the Belfast Lough experiment has been anlaysed to obtain relationship between wind speed, fetch, buoy hydrodynamics and turbine generator performance. The results have been correlated with those from tenth scale model tests in the university wave tank. The experience gained from the sea trials has been invaluable in the development of the further pre-production prototypes.

The team consider the navigation buoy work to be a significant first step towards larger wave power devices. Even within the field of navigation aids in general there is a geometric progression of power demand from a few watts for small buoys to tens of kilowatts for manned light-houses. The lighthouse authorities are keenly interested in using alternative energy sources to supplement conventional fuel supplies provided they are reliable and economically viable. The use of wave power for lighthouses would provide a convenient step towards 50- and 100-kW units for supplying island communities.

The use of wave power for island communities and the natural progression from navigation aids has already been recognised by the Japanese. During the past year, they have installed a 40-kW Wells turbine on an oscillating water column device constructed on the shore line in a rock gully. Electrical power is being supplied to the grid system. The Norwegians are also keenly interested and recently announced that in the next few years they would be building a 400-kW oscillating water column device mounted in a rock face incorporating a Wells turbine.

TJTW & DSM

APPENDIX B

B 1 Status of latched power buoy

Notes by J. Falnes

Energy recovery time < 2 years

(better than other devices)

Labour required for construction and maintenance

(more than with other devices)

More development work necessary on the moving parts of the device

Design study and laboratory testing of models of the moving parts finished early 1983

Further development requires testing in sea in nearly full scale. Funding for continued research is missing.

The group in Trondheim continues its research on wave power.

- Theory and simulation studies
- New ideas, for instance, phase control of oscillating water columns
- Development of mini wave-power buoys (1W-1kW)

B2

S T A T U S 1983 O F

T H E N O R W E G I A N

W A V E - P O W E R B U O Y P R O J E C T

by

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STATUS 1983 OF THE NORWEGIAN WAVE-POWER BUOY PROJECT

Introduction

Three years ago we brought forward a particular proposal of a wave-power buoy,[1, 2] which has been a substantial part of our research topic during recent years. The project has received financial support through Olje- og energidepartementet (The Royal Ministry of Petroleum and Energy). The engineering aspects of the project have been coordinated through the research consortium OTTER (Offshore Technology Testing and Research) in Trondheim.

Design of a power buoy in full scale

The OTTER project coordinator T. Hals has produced a report (STF88-F82060) "Prosjektering av bølgekraft-bøye type N2" ("Projecting wave-power buoy of type N2") with 14 appendices. The report (which is restricted) contains details on the design, on laboratory testing of mechanical components, on reports from technical consultants, and on offers from industrial firms. This document would form the basis for asking for tenders with the purpose of constructing a test buoy in full scale. It is expected that the buoy would function with a reasonable degree of reliability during a testing period of two to three years, provided the functioning of the critical components are sufficiently tested before installation. However, it is emphasised that substantial development and testing of components have to be carried out before reliability and lifetime have reached a level which is acceptable for a power plant.

Economic assessment

In 1981 an official assessment[3,4] of a 200 MW wave-power plant off the western coast of Norway was made in four different alternatives. It was based on the state of industrial construction and enterprise in Norway in 1981. The estimated cost of produced energy was in the region 1.20 - 1.40 kr/kWh (£ 0.11 - 0.13/kWh) for three different Norwegian device proposals and 2.30 kr/kWh (£0.21/kWh) for a British proposal (the bottom-standing NEL oscillating water column). Note that independent British assessments present much lower cost estimates for the NEL device. The reason for the discrepancy may be, firstly, the high cost of labour in Norway, secondly, the lower figure of average incident wave power per unit length of the Norwegian coast, and thirdly, that future developments of the device and of the construction technology were not taken into consideration.

For a 200 MW plant consisting of 410 wave-power buoys the official assessment[2,3] gave an energy cost of 1.40 kr/kWh (£0.13/kWh). A breakdown of the cost is shown in Table 1 (columns marked "EVA2"). We have made an alternative assessment[1,5] which results in lower cost as shown in the same table (columns marked "TEAM"). We present cost figures in a range, where the higher figures correspond to the first generation plant, while the lower figures indicate cost reduction after many large wave power plants have been constructed. The given cost figures are commented and justified elsewhere[1,5]. We shall, however, present some additional comments to Table 1.

In 1981 a Norwegian ship yard informed us that the construction of one unit of the hull in welded steel would cost 14 kr/kg. For our highest figure we assumed 20 % reduction for construction of 410 units, whereas the EVA2 figure is based on 22 kr/kg. An updating[6] of the official assessment for one piece of an oscillating-water-column structure in welded steel indicates a normal cost of 14 kr/kg, but with the depressed market situation in 1983 a cost of 9,50 kr/kg seems now realistic. Under these circumstances it is believed that the TEAM's highest figure in Table 1 is rather conservative.

The above-mentioned updating[6] claims that small units of wave-power devices in Norway can deliver energy at half the cost given in the former assessment[3,4].

Half of the EVA2 figure for miscellaneous and contingency is due to cost of facilities for construction of anchors and for assembling and cost for levelling the sea bed. We did not include such costs in the TEAM figures since our cost figure for the gravitation anchor was based on an offer from a Norwegian firm, and since gravitation anchors can be used also in locations where the sea bed is naturally flat.

A report "Elsystem för vågkraftverk, utforming och kostnadsberäkning för ett bojkraftverk vid Bremanger" ("Electric system for wave-power plant, design and cost estimate for power-buoy plant at Bremanger") by Å. Kinnander, (report no. 82-112 from Technocean AB) in 1982 states that a DC transmission system for the power plant would cost approximately 0.1 Gkr. This indicates that the higher figures in Table 1 are conservative, in particular since AC transmission was assumed in the former assessment[3,5].

Finally, we mention that the official 1981-assessment[4] has been commented both by us[1,7] and by an independent Swedish consultant[8].

Energy recovery and labour

Energy and labour are resources which are required in order to make a product. The energy associated with 100 ton of steel is approximately 1.1 GWh. Thus, during approximately one year each buoy will recover the energy contained in the steel of the hull and the strut (cf. Table 1). We expect[7] that the total recovery time for the energy invested in the power-buoy plant is less than two years. This is much shorter than the energy recovery time for other proposed wave-power devices. For two other proposed Norwegian devices the energy recovery time is estimated[3] to be 10 to 14 years.

However, the labour invested in the power-buoy plant is relatively large. Also since the phase-controlled power buoys contain some critical moving parts, it is believed that relatively much labour is required for operation and maintenance, compared to the other assessed devices. This may have a positive effect for the employment in the coastal areas where the power-buoy plant is located.

Future development and full-scale testing of the power-buoy device in the sea are required before we know decisively that the maintenance will not be excessively expensive.

Model tests

A model in scale 1:10 has been tested[9,10] in the sea near Trondheim, during six periods between September 1981 and June 1983. It was in the sea 170 days altogether. After the first periods modification had to be made, in particular on the guiding rollers, the latching mechanism and the measuring equipment. The system functioned satisfactorily during the two final test periods. Between those two periods the opening in the bottom of the buoy was modified in order to reduce viscous losses at the entrance.

Results from 14 different records taken during the sixth testing period are summarised in the diagram of fig. 1. The corresponding wave heights and periods are in the regions 0.08 - 0.4 m and 2.8 - 3.6 s, respectively. The measured input power is the sum of pneumatic power in the pump chamber and a relatively small contribution, the power lost in friction between the buoy and its mooring strut.

Conclusion

Several official assessments[3,4,6] of wave-power plants in Norway show decreasing figures for the estimated cost of wave energy. The latest updating[6] seems to confirm some of the points in our own assessment[1,5] of a phase-controlled power-buoy plant, where we estimate the energy cost to be roughly 0.6 kr/kWh (5 pence/kWh) which has prospects to be reduced to 0.3 kr/kWh (3 p/kWh) in the future. This cost would be competitive on national energy supply markets.

Among many different assessed wave-energy devices the phase-controlled power buoy is outstanding in having a rather low investment of energy, materials and money in relation to the produced energy per year. On the other hand, relatively much labour is required to construct and maintain the plant.

Since the device contains some critical moving parts, more development work and full scale testing in the sea are required in order to obtain acceptable lifetime and reliability.

Such a development program should be started as soon as possible. The program may result in knowledge on how to design a reliable device.

Our project has been pursued with design work to a stage where the next step is to construct a full-scale test buoy. However, since funds for such work are not yet available, our research team now continues its work on other aspects of wave power, i.a. work on mini-power devices and on phase-control of oscillating water columns.

Trondheim, 1983-10-26

Kjell Budal　　Johannes Falnes

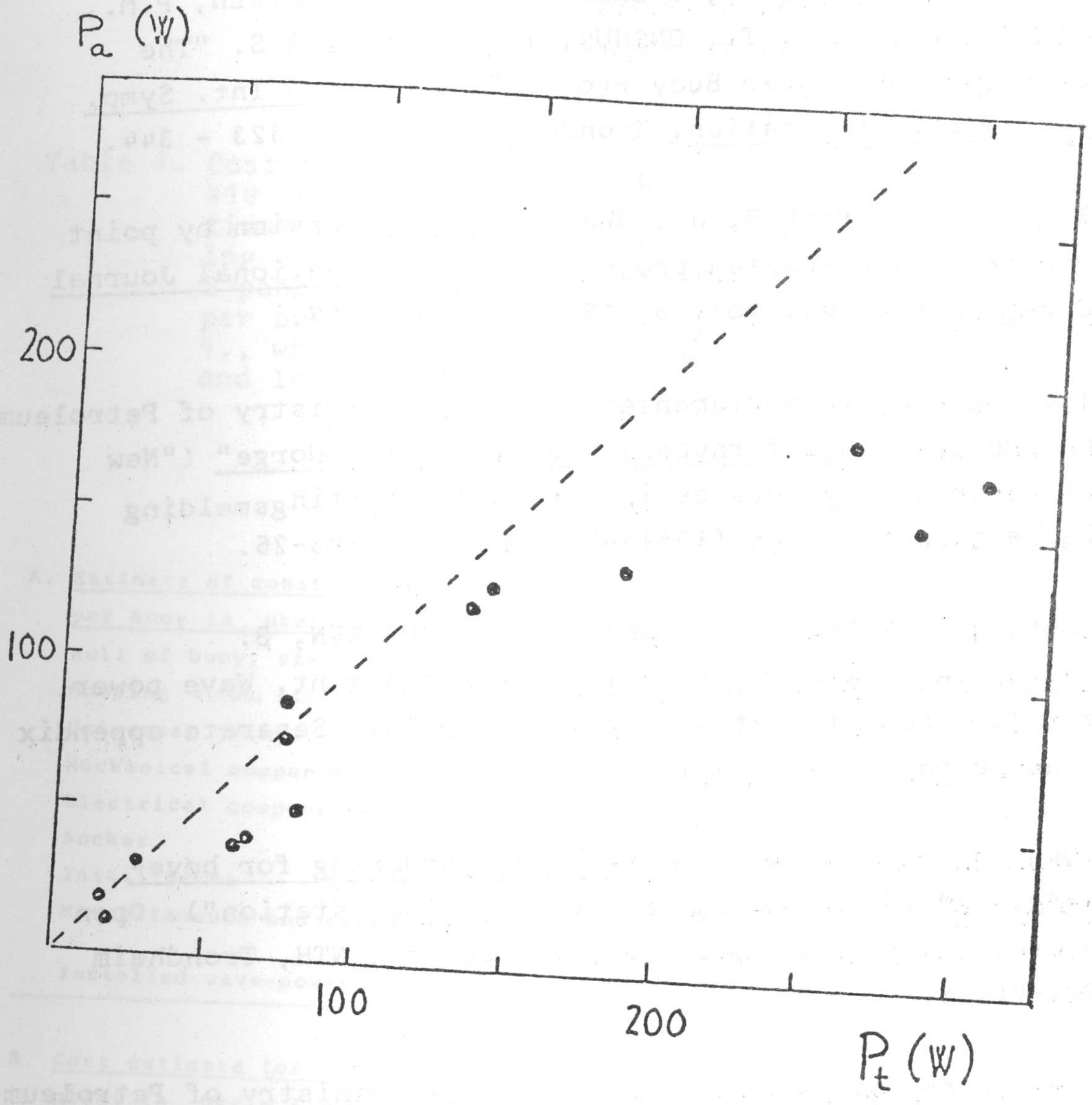

Fig. 1. Results from sea tests[9,10] of power-buoy model in scale 1:10. The vertical scale gives the measured input power P_a to the buoy. The horizontal scale gives theoretical values as given by using measured values of the wave and of the heave motion in a theoretical formula. For input power below 130 W (corresponding to 0.4 MW in full scale) there is reasonable agreement between theory and experiment since the experimental points are fairly close to the inclined dashed line.

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2. BUDAL, K. and FALNES, J., "Wave power conversion by point absorbers. A Norwegian project", The International Journal of Ambient Energy, vol. 3, 1982. pp. 59 - 67.

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5. BUDAL, K., and FALNES, J. "Kostnadsvurdering for bøye-kraftverk" ("Cost estimate for buoy power station"). Open report, Division of Experimental Physics, NTH, Trondheim 1982-01-18.

6. Olje- og energidepartementet (The Royal Ministry of Petroleum and Energy). "St. meld. nr. 65 (1981-82) om nye fornybare energikilder i Norge. Oppdatering". ("White paper no. 65... Updating"). Letter to Stortinget (The Norwegian parliament) dated 1983-02-22 including two enclosed reports, one of them entitled "Evaluering bølgekraft. Kostnader for små kraftverksenheter" ("Assessment wave power. Cost of small power-producing units") issued 1983-02-01 by Kvaerner Engineering A.S.

7. BUDAL, K. and FALNES, J. "Kommentarar til stortingsmelding nr. 65 (1981-82): Om nye fornybare energikilder i Norge" ("Comments to white paper no. 65...", ref.3). Open report, Division of Experimental Physics, NTH, Trondheim, 1982-04-28.

Table 1. Cost estimate for 200 MW power plant consisting of 410 wave-power buoys. The left-hand columns give estimated cost and the right-hand columns give corresponding cost per unit of produced energy in kr/kWh (1 kr = 9 pence), assuming an energy production 1 GWh/year per buoy. Columns mared EVA2 are based on refs. 3 and 4., while columns marked TEAM are based on the higher and lower cost figures given in ref. 1 or ref. 5.

	EVA2	TEAM	EVA2	TEAM
A. Estimate of construction cost per buoy in Mkr = £ 9.10^4	Mkr	Mkr	kr/kWh	kr/kWh
Hull of buoy, steel, 45 tons	1.5	.6 - .3	.14	.06 - .03
Mooring strut, steel, 53 tons	.4	.32 - .22	.04	.03 - .02
Universal joint, ± 30°	.3	.14 - .1	.03	.01 - .01
Mechanical components	1.0	.9 - .5	.10	.08 - .05
Electrical components	.2	.2 - .16	.02	.02 - .02
Anchor	1.3	.8 - .2	.12	.07 - .02
Installation	.7	.6 - .3	.06	.06 - .03
Miscellaneous and contingency	1.2	.3 - .2	.11	.03 - .02
Installed wave-power buoy	6.6	3.8 -2.0	.62	.35 - .19
B. Cost estimate for 200 MW plant in Gkr = £ 9.10^7	Gkr	Gkr	kr/kWh	kr/kWh
Construction and installation of 410 buoys	2.7	1.5 - .8	.62	.35 - .19
Electrical transmission	.24	.12 - .07	.05	.03 - .02
Interest and other costs	.4	.1 - .05	.09	.02 - .01
Investment tax, 10 %	.3	.16 - .09	.07	.04 - .02
Invested capital for power plant	3.6	1.9 - 1.0	.83	.44 - .24
C. Annual costs in Gkr = £ 9.10^7	Gkr	Gkr	kr/kWh	kr/kWh
Capital 9.44 % (7 %, 20 years)	.34	.18 - .10	.83	.44 - .24
Operation and maintenance	.23	.06 - .03	.56	.14 - .08
Total	.57	.24 - .13	1.39	.58 - .32

8. HARDELL, R. "Economic assessments of wave energy production in buoy systems". Proc. 2nd Int. Symp. Wave Energy Utilization, Trondheim 1982, pp. 297 - 304.

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10. IVERSEN, L.C. and LILLEBEKKEN, P.M. "Modellforsøk med N2-bøyen i Trondheimsfjorden våren 1983" ("Model test of the N2 buoy in the Trondheim fjord during the spring 1983") Open report, Division of Experimental Physics, NTH, Trondheim June 1983.

B3 KVAERNER's multiresonant OWC

(differs from NEL's OWC

- point absorber, not line absorber
- protruding side walls, "harbour")

Blasting shelf in rock 12 x 12 m down to - 8m

(tidal range < 1m)

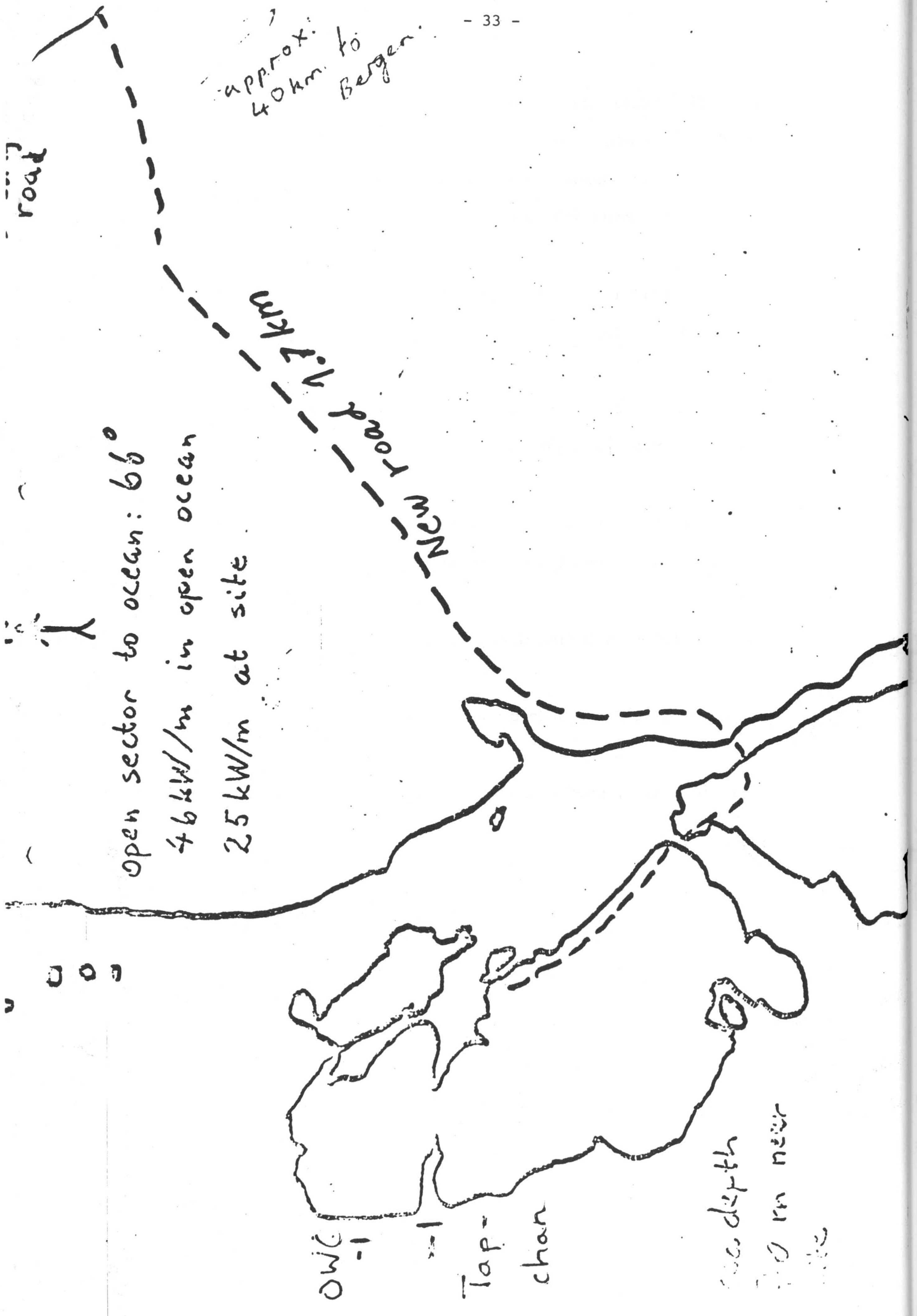
Inner width of steel chamber 10m installed October 1984 with orifice to measure pneumatic power

350 kW Wells' turbine and generator installed August 1985 and produced electricity connected to grid.

Budget £1.0 M including design etc.

Estimated cost for a second unit: £.3 M

Estimated energy production 1 GWh/year



A NORWAVE's Tapchan Wave-Power device

Tapered channel blasted in rock down to -7m

Total length - 170m

Except for 60m length in the wide end, concrete walls will be built from -7m to +3.3m

Basin 5500m^2 to store energy (~ 4 min)

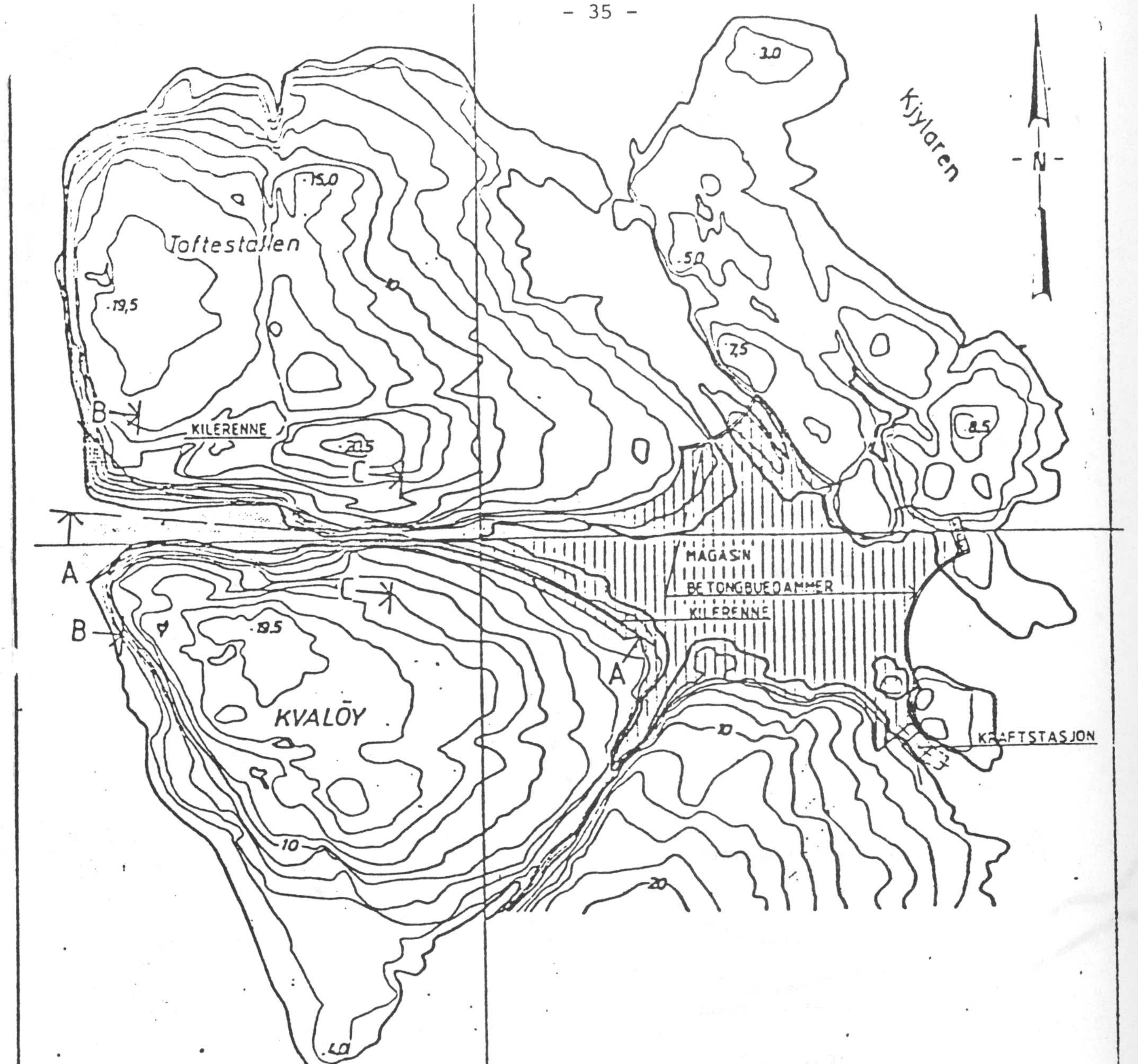
Kaplan turbine 350kW

head 3m (vertical range .6m)

Estimated energy production 1.8 GWh

Estimated cost M£

Tapchan	.26
Basin	.08
Power station incl. turbine & generator	.33
Miscellaneous	.11
	.78
+ Estimated cost of road	.11
Estimated energy cost	(7% interest, 25 years)
Prototype alone	4.7
1.7km	.7
	5.4



SITUASJONSKART
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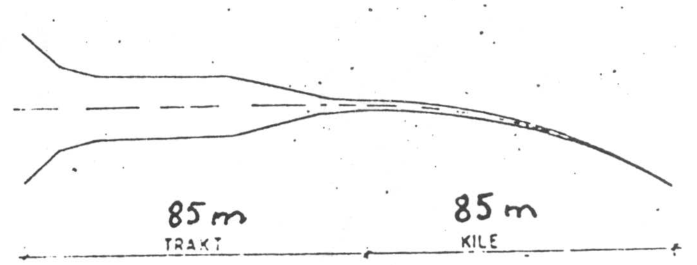

PLAN AV KILERENNE
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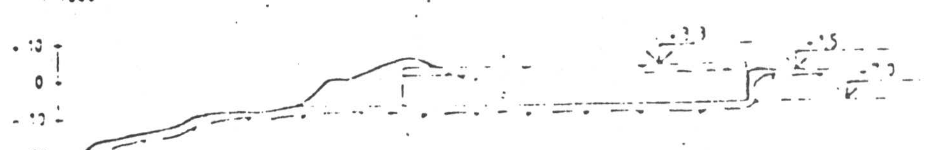

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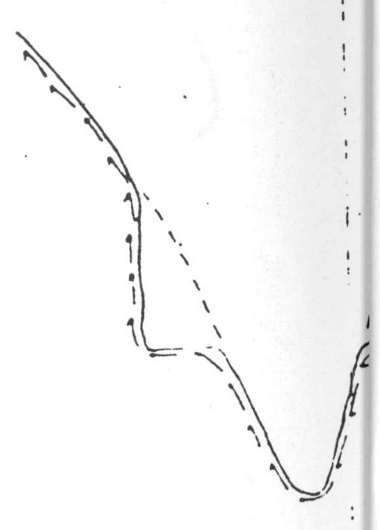

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Appendix C

Notes on work on wave-power at University of Lancaster

1. Work stopped on the Flexible Bag device at the end of 1982. Although the last part of the programme promised a return to earlier power levels, of nearly double the reference design figures the cost of the device was simply too high. Moreover, the prospect of these huge WEC's ever being developed at full scale seemed remote with the receding of the energy crisis.

2. Flounder, a system of 'small' bodies moving in surge relative to one another, promised lower costs and a very much lower development cost. However, the next device, Frog, seemed even more attractive.

3. Frog is a simple buoy reacting in heave against an internal moving mass. It has the virtues of being small, self-contained and all enclosed in a steel shell without moving parts. It has engineering problems, notably the 'suspension' of the moving mass, but we believe these are far from insuperable. We have just signed an agreement with the Department of Energy for a small, one-year programme, basically, a design study. The programme includes also the study of a variant about which we have not yet formed a view, but the original concept remains attractive and we believe it might be capable of producing power at low costs (e.g., about 3p/kWh) and above all, with low development costs.

4. The situation has changed little since our last note (TN 31, 22/11/82) but the small programme we have run, without outside funds, has increased our confidence greatly. Above all we have confidence in the estimated power output, and we think we have a good workable answer to the worst engineering problem.

MJF

19 June 1984

APPENDIX D

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REF:
(which kindly quote)

11/7/84

THE MAURITIUS ('PASSIVE') WAVE-ENERGY PROJECT: A BRIEF SYNOPSIS OF ITS HISTORICITY AND PRESENT STATUS

Historicity

Following the setting up of the Mauritius Central Electricity Board (CEB) in 1952 it was quickly realised that the only two indigenous energy sources - River-hydro and Sugarcane 'bagasse' - would soon become absorbed, leaving the Island dependent on imported oil.

The abundant and steady wave-energy around its coasts appeared to offer a permanent long-term solution, a view confirmed by a CEB in-house study team adopting the 'impounding' (or 'passive') system. The Mauritius Government and CEB decided therefore to seek professional outside opinion and the UK Dept. of Technical Cooperation (now ODA) agreed - with commendable faith and foresight - to make a grant of £5,000 (1956) to cover the above services.

The project has thus been under study and examination for over a quarter of a century and has been the subject of 3 official Reports by one of the UK's oldest and well known Hydro-electric Consultants. All 3 Reports confirmed technical feasibility but it was not until after the 1973 oil crisis that 'economic' viability could be established as confirmed by the Consultants 3rd Report (1975). On a cost per Kwh basis the balance in favour of wave-energy at that time was marginal but over the years this has increased in real terms and like almost all hydro projects will continue so to do with time.

Following this latter Report the Mauritius Govt./CEB made representations to the UK/ODA for a further grant of £60,000 to cover the cost of certain pre-construction foundation tests at the proposed site. Despite the prestige of the Consultants concerned; despite the former grant by ODA; and despite the growing energy problems of Mauritius, an ODA Assessment Panel summarily dismissed the application (1975). But for this disastrous decision it is highly likely that a wave-energy project could have already been in commission over a period of 4/5 years with incalculable effects on the course not only of wave-energy research in the UK but also on British trade and industry and all the 3rd World Countries who now find themselves in the predicament of Mauritius. The 'Assessment Panel' concerned has much to answer for.

/Over - -

By 1981 the CEB total generation output had reached 360GW some 65% of which was supplied by oil and with the situation worsening by the year. The Mauritius Govt. again approached the UK for financial assistance to provide an updated Consultancy Report, carry out the pre-construction tests and generally bring the project to 'Tender Stage'. Through the offices of the Crown Agents consultations took place between London, The European Development Fund (EDF), Government of Mauritius and several other Indian Ocean Islands including Seychelles, Madagascar, Comoros, it being eventually decided that as research had been concentrated on Mauritius this would be the obvious site for the prototype project.

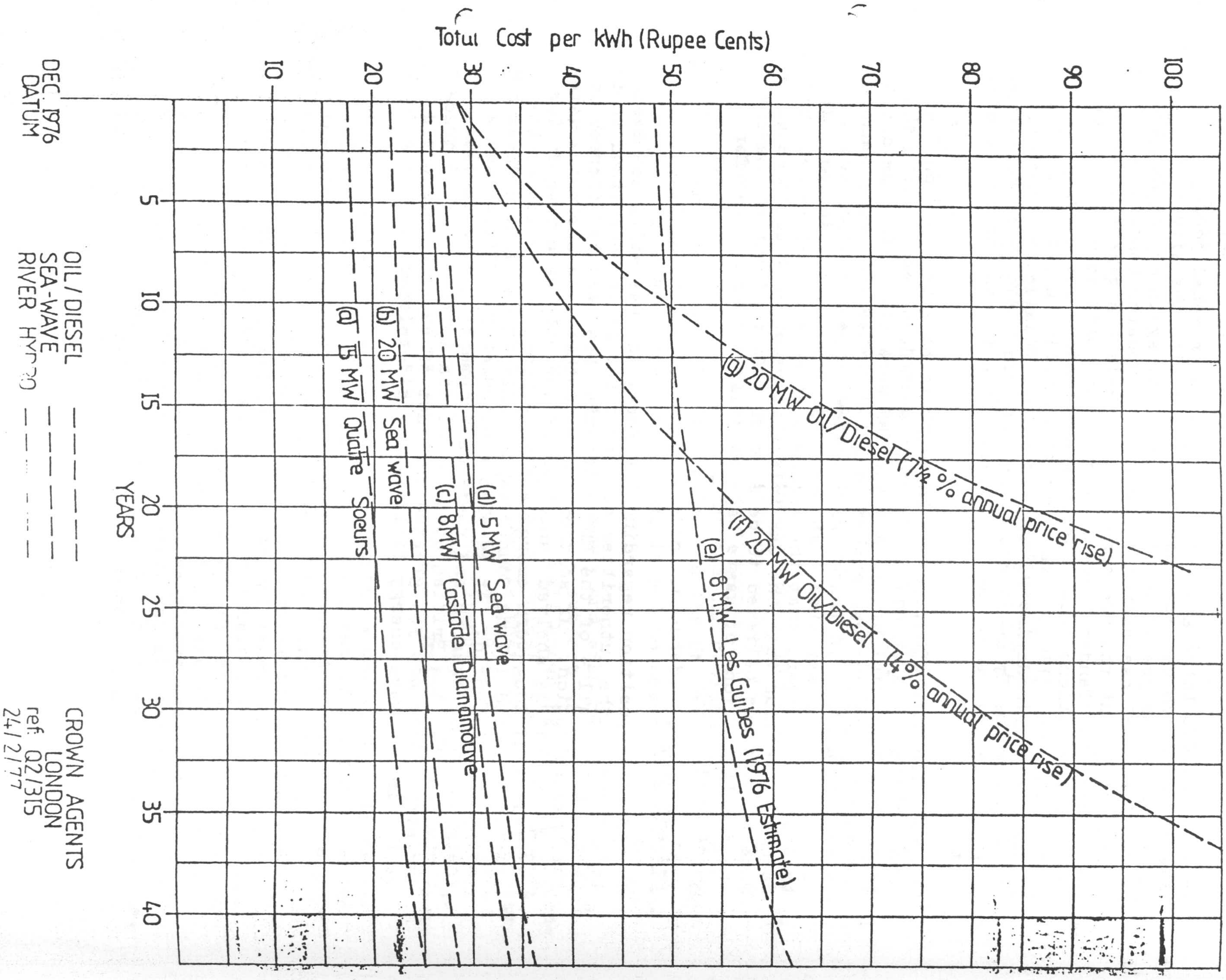
The EDF allocated $500,000 for the work in November 1982 but in December there was an unexpected change of Government, which then declared a financial crisis and the IMF were called in. As a consequence the project was shelved until November 1983 when consultations took place in London with a view to reactivating the project and it then appeared that the project would go forward. It transpired, however, that the economic effects of oil imports had become so serious that the CEB felt that recourse would have to be made to what was believed to be a quicker form of relief, namely, the 'pellitization' of waste bagasse still not being used for power generation.

Present Status

The official position regarding the foregoing has still not been made clear by the Authorities concerned but it is understood that part - if not all - of the EDF allocation has been transferred to the 'bagasse' option. If so, then it means that once again the wave-energy project is shelved, which would not only be a tragedy for the Mauritius long-term energy strategy but also for those other similarly placed island Countries, not only in the Indian Ocean but throughout the world. It is also a set-back for British wave-energy systems research and their development; it would seem therefore that the British Govt. - especially the Dept. of Trade & Industry - have not yet grasped the fact of the enormous world market in the wave-energy field awaiting development.

GRAPH SHOWING RELATIVE COSTS PER KWH IN RESPECT OF
(a) SEA-WAVE (b) OIL / DIESEL (c) RIVER HYDRO POWER

Note: Oil diesel curve (f) is based on price increase of 4% per annum only
(g) 7½%



WAVE POWER - ESTIMATED WORLD ELECTRICAL OUTPUTS, OIL EQUIVALENTS AND CAPITAL COSTS CORRESPONDING TO VARYING ASSUMED DEGREES OF COASTAL DEVELOPMENT

Coastal development (kms) as a % of total	Power output in (KW)	Energy output in (KWH)	Oil equivalent Per annum	(Million barrels) per day (MBD)	Capital Cost (a) £ Sterling (b) US Dollars
See footnote (i)	See footnote (ii)	See footnote (iii)	See footnote (iv)	See footnote (v)	See footnote (vi)
(A) 25,000 (5%)	125 Million (125×10^6)	1.375 Mill. Mill. (1.375×10^{12})	3274 MBD	9 MBD	£125,000 Mill. $250,000 Mill.
(B) 50,000 (10%)	250 Mill. (250×10^6)	2.750 Mill. Mill. (2.750×10^{12})	6548 MBD	18 MBD	£250,000 Mill. $500,000 Mill.
(C) 75,000 (15%)	375 Mill. (375×10^6)	4.125 Mill. Mill. (4.125×10^{12})	9822 MBD	27 MBD	£375,000 Mill. $750,000 Mill.
(D) 100,000 (20%)	500 Mill. (500×10^6)	5.50 Mill. Mill. (5.50×10^{12})	13096 MBD	36 MBD	£500,000 Mill. $1000,000 Mil.
(E) 125,000 (25%)	625 Mill. (625×10^6)	6.875 Mill. Mill. (625×10^{12})	16370 MBD	45 MBD	£625,000 Mill. $1250,000 Mil.

Note (i) Coastline percentages based on total world coastline of 500,000 kms. including all islands.

(ii) Power output based on Mauritius research figure of 5KW per metre wave front.

(iii) Energy output based on Mauritius research figure of 50,000 KWH per metre wave front

(iv) Oil equivalent based on 1 - UK barrell = 420 KWH

(v) 40 MBD is equivalent to about one half of the worlds estimated total energy demand as at 1980.

(vi) Calculated @ $2 = £1 Sterling.

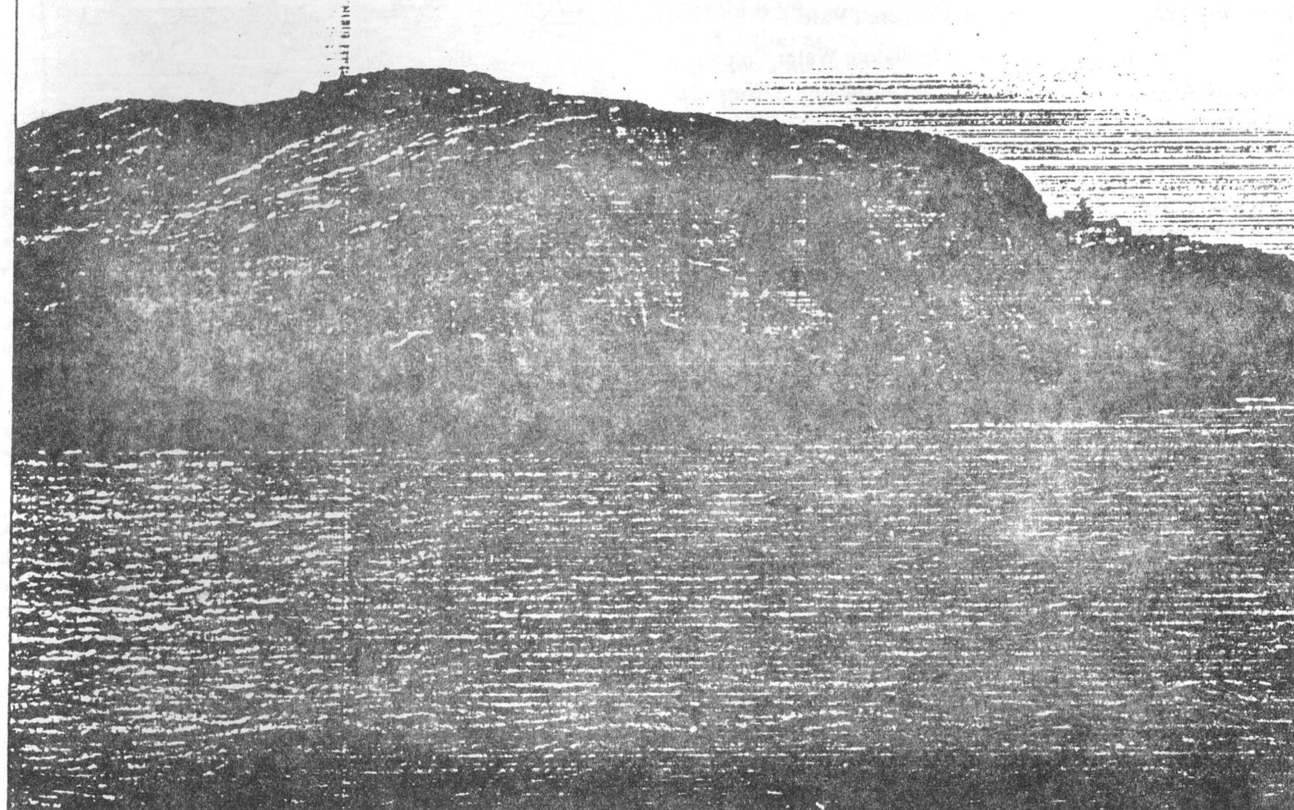
WAVE-ENERGY 'PASSIVE' (OR LAGOON) SYSTEM
LIST OF OFFICIAL REPORTS, PAPERS AND OTHER DOCUMENTS

Ref:No.	Document Title	Author(s): Firm, etc.	Sponsor(s)	Recipients or Publications
OFFICIAL REPORTS				
(1)	'Electricity Supply-Sea Power' (A first appraisal following a 2 year study).	A.N.Walton Bott (as Gen. Manager & Deputy Chairman, Central Electricity Board, Mauritius.	Central Electricity Board, Mauritius.	Government of Mauritius (1958).
(2)	'Mauritius Wave Power Scheme'	Sir Alexander Gibb & Partners, London.	U.K. Department of Technical Cooperation, London.	Government of Mauritius through Crown Agents, London (1959)
(3)	'Mauritius Wave Power Scheme - Model Investigation'	Hydraulics Research Station, Wallingford, U.K. (Dept. of Scientific & Industrial Research).	U.K. Department of Technical Cooperation through Crown Agents.	Sir Alexander Gibb & Partners & Government of Mauritius (1960).
(4)	'Mauritius Wave Power Scheme'	Sir Alexander Gibb & Partners, London.	Central Electricity Board, Mauritius.	Central Electricity Board, Mauritius (1966).
(5)	'Estimates of Accounting Prices Mauritius'	M.F.G. Scott, Nuffield College, Oxford.	Government of Mauritius	Government of Mauritius (1972).
(6)	'Mauritius Wave-Energy Project - Feasibility Study'	Sir Alexander Gibb & Partners, London.	Ministry of Overseas Development (formerly Department of Technical Cooperation - now Overseas Development Administration).	Government of Mauritius & Crown Agents, London (1976).
OTHER PUBLISHED DOCUMENTS				
(7)	'Fish & Shell-Fish Farming in Coastal Waters'	Dr. P.H. Milne, Department of Civil Engineering, University of Strathclyde.	Fishing News (Books) Ltd. Fleet Street, London, U.K.	Available from Publisher (1972).
(8)	'Power Plus Proteins from the Sea'	A.N. Walton Bott	Royal Society of Arts, London.	Royal Society of Arts (RSA Journal of July 1975).
(9)	'The Development of Fish-Farming'	Various	Royal Society of Arts, London.	Royal Society of Arts Symposium Report (1975).
(10)	'The Development of Wave Power A Techno-Economic Study'	National Engineering Laboratory, East Kilbride, Scotland, U.K.	U.K. Department of Energy, London.	U.K. Department of Energy & Central Government, (1975).
(11)	'Renewable Sources of Energy'	Various	Royal Society of Arts, London.	Royal Society of Arts Symposium Report (1976).
(12)	'Wave Power Prospects for Mauritius'	A.N.W. Bott: J.S.M.Hailey: P.D. Hunter	I.P.C. Electrical Press Ltd. London.	'International Water & Dam Construction' Journal of December 1978.
(13)	'Wave and Tidal Energy'	A.N.W. Bott: J.S.M.Hailey; P.D. Hunter	BHRA Fluid Engineering, Cranfield, Bedford, U.K.	International Conference & Symposium at University of Kent, Canterbury, UK (1978).
(14)	'Wave-Energy Scheme, Mauritius'	Sir Alexander Gibb & Partners, Reading, U.K.	Sir Alexander Gibb & Partners.	For general circulation (1979).
(15)	'Wave and Tidal Energy for Developing Countries	A.N. Walton Bott & E.D. Lawrence - Crown Agents.	British Council: U.K. Solar Energy Society: Crown Agents, London.	Conference on 'Small-scale Energy for Developing Countries' at University of Reading, U.K. (1979).
(16)	'The Mauritius Wave-Energy Project'	R.J. Leicester, Crown Agents.	I.P.C. Electrical Press Ltd. London.	International Power Generation Journal U.K. (April 1980).
(17)	'An Assessment of the Potential for Wave-Energy systems in	A.N. Walton Bott & R.J. Leicester.	E.D.F. through University of S.Pacific and U.N. Development Programme.	ESCAP Energy Conference Apia, W.Samoa (1980).
(18)	'Electro-Mechanical aspects of Mauritius 'Passive' type	A.N. Walton Bott, Crown Agents.	Institute of Electrical Engineers, London, U.K.	International Conference on 'Future Energy Concepts' at Institute of Electrical Engineers, London, U.K. (1980).
(19)	'A Rising Tide for Wave-Energy'	J. Platts, Wavepower Ltd. Southampton, U.K.	I.P.C. Electrical Press Ltd. London.	International Power Generation Journal of April 1980.

APPENDIX E

The troughs and crests of wave energy

by Dr Michael Flood*



Official interest in wave energy began to develop in the UK around 1974 in the wake of the first OPEC oil crisis. A quadrupling of oil prices and a nudge from the Central Policy Review Staff prompted the Government to commission an investigation into the prospects for the large-scale generation of electricity from ocean waves. This review, conducted by the National Engineering Laboratory and completed in May 1975, concluded that the country's wave energy resource certainly did warrant further detailed examination.

Later this summer Norway will commission two prototype wave energy stations at a coastal site 25 miles north west of Bergen. All indications are that these stations, which have been built both to time and to cost, will provide competitively-priced electricity and could open up a lucrative export market for Norway. Two of the country's leading wave energy experts have recently returned from a promotional tour of the South Pacific. The United Kingdom, which has done so much to advance wave energy technology (Table 1), looks like missing the boat. This article reviews the world wave energy sea state in the light of the changed circumstances of today.

A small £1 million programme was set in hand under the newly created Energy Technology Support Unit at Harwell and four out of a total of 30 novel wave devices were singled out for special study. These were the Salter *Duck*, the Wave Contouring Cockerell Raft, the Russell Rectifier and the Oscillating Water Column 1. The objective was to design a wave power station that would be capable of capturing 2 GW of power from the sea off the Outer Hebrides and delivering it economically to the national grid. Official thinking 2 envisaged that, with a vigorous development and exploitation programme, wave energy might contribute the equivalent of *half* of today's electricity demand by 2025 (around 120 TWh/yr).

In 1978/79 a second generation of systems appeared, including the Lancaster Flexible Bag and the *Clam* 1, and these too received official backing. Wave energy was officially accorded high priority amongst 'new' sources of energy and considered 'the most attractive of the renewable resources' 2. Annual expenditure rose from around £0.2 million in 1976 to £4.4 million in 1982 and within less than a decade, the UK had become the world leader in this new technology.

Cost problems

However, at this point things started to go badly wrong. The Government wanted quick results and work appeared to be progressing slowly as teams wrestled with the dual problem of increasing efficiency and reducing costs. Nobody doubted that wave energy converters could be built, nor that they would work. The problem was one of cost. Several devices

* Dr Flood is a freelance energy consultant. He has organised two national wave energy seminars at the Open University and is an adviser to the Friends of the Earth on renewable energy technologies.

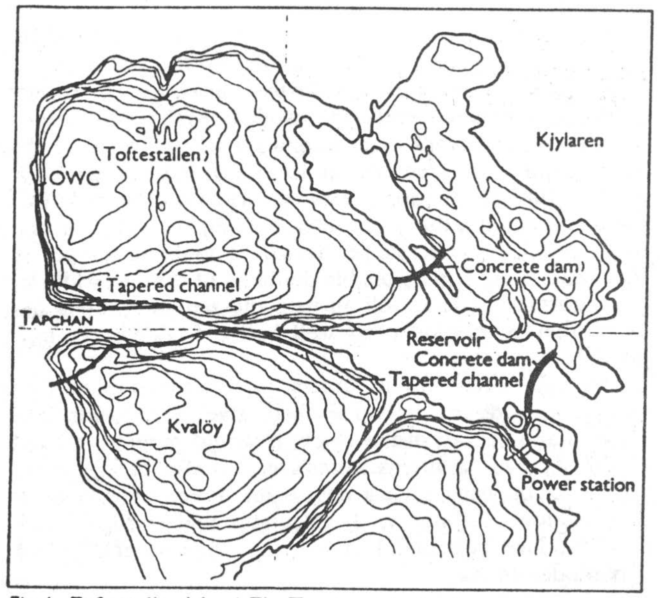


Fig 4. Toftestallen Island. The Tapchan inlet has been shaped to form a tapered channel around 170 metres long which funnels breakers up a ramp and over a low dam. The wave height is amplified as the waves propagate along the channel until the wave crests spill over the dam walls. The overspill is impounded in an artificial reservoir created by damming two other small inlets. Power is generated by discharging the impounded water back to sea via a conventional Kaplan turbine. Tapchan's promoters say that the concept is adaptable for plants sized between 0.5 and 3000 MW but that the economy is highly dependent upon local variations in the wave energy. Key parameters, such as capital cost per installed kW and unit cost vary with installed machine capacity so optimisation of parameters is a very important part of design. Norwave uses a computer program, Wavetrack, to analyse the local wave climate

to the mainland grid although its performance was somewhat disappointing and it has since been substantially modified below the water line.

Later this summer Norway plans to commission two small wave energy stations which have been built on the island of Toftestallen about 25 miles north west of Bergen. Both projects are 50% government funded. The first, designed and built by the engineering firm, Kvaerner Brug, is a point absorber OWC; the second, known as 'Tapchan', (short for 'tapered channel'), has been developed by the Norwave Consortium and the Central Institute for Industrial Research in Oslo (see 'Norway on the crest').

The two projects are rated at 500 kW and 350 kW respectively and are expected to generate electricity at below 5 p/kWh. They cost, together, and including an access road, around £2 million. At 5 pence per unit, wave energy would be roughly twice the cost of hydro-electricity in Norway – domestic consumers pay around 2.7 p on average. However, 5p is only half the cost of diesel generation. On the strength of model tests the Kvaerner device is actually predicted to generate at 3.4 p/kWh, and there are indications from the flow tests on the prototype that it may well be cheaper than this. But these figures have yet to be confirmed by actual practice.

Norway has proceeded with wave energy with an eye to both the home and the export market. It has already used up most of its cheap hydro sites and anticipates that future installations will be considerably more expensive to build. On the other hand, she expects wave energy costs to come down as experience is gained. So far as exports are concerned, Kvaerner has already entertained delegations from China and elsewhere (including the UK) and two of its top experts, Knut Boenke and Jan-Erik Steen, have recently returned from a tour of the South Pacific where they visited possible sites in Western Samoa, Tonga, the Cook Islands and Fiji **9**.

What next?

Where, then, does the future of wave energy lie? The answer to a large extent is now out of the UK's hands. Much will depend on the success of the Norwegian and Japanese work and the extent to which other countries get involved. A straw poll held at last year's Wave Energy Seminar at the Open University indicated that over 40 researchers were active abroad in countries as far apart as Australia, Brazil, France, India, and Portugal **10**.

If the Norwegian prototypes perform well and produce the cheap power that is expected they could open up a lucrative export market for small wave power devices. Several countries have expressed an interest in buying them. Once this market is established it may then be appropriate for wave energy researchers to venture back into deeper waters where the power densities – and the problems – are greater. Whether UK teams are able to compete in this work and receive the recognition that they deserve, will depend to a large degree on the official support that they receive. On the evidence of the last couple of years the prospects of this happening do not look good. □

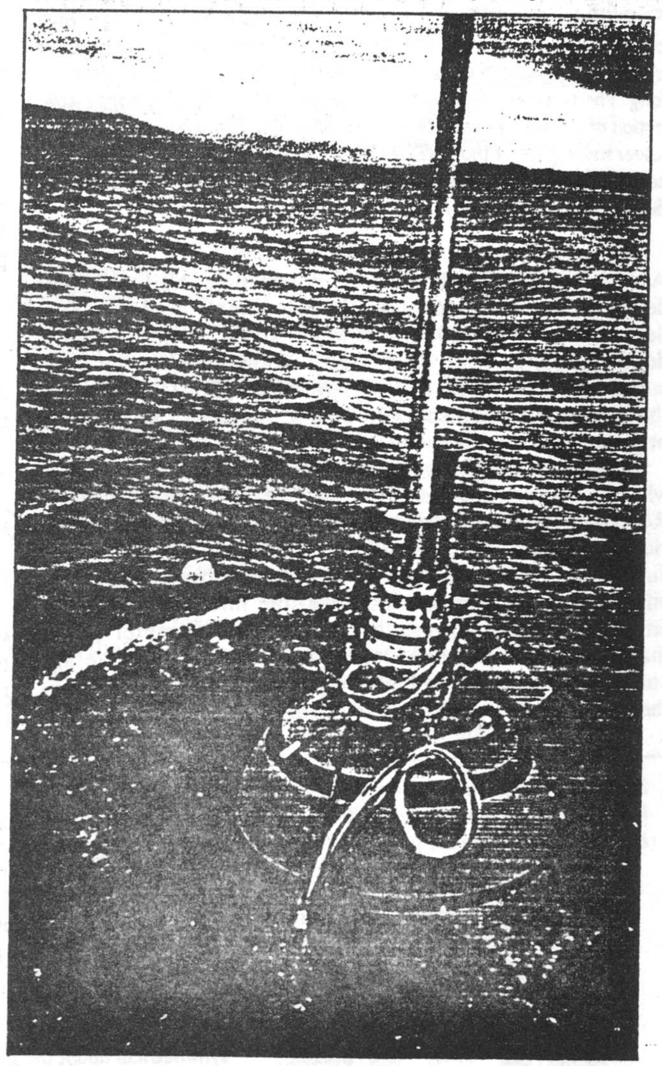


Fig 5. The phase-controlled power buoy. It consists of an almost spherical bell which is open to the sea at its lower end. A rigid vertical shaft passes through the centre of the buoy and down to a universal joint anchored firmly to the sea bed. The waves cause the buoy to travel up and down the shaft on roller bearing and this motion forces air through a turbo generator mounted inside the top of the bell. It has an intelligent control system called 'latching'. The buoy is clamped to the shaft momentarily at the top and bottom of each stroke so that it executes a jerky motion rather than a smooth natural oscillation. Sensors detect the pressure of incident waves and this information enables an onboard computer to determine when the buoy should be clamped or released so as to achieve the maximum stroke amplitude. Model tests indicate that conversion efficiencies of 80% might be achieved in large buoys with outputs in the 100–400 kW range

Norway on the crest

Norway's interest in wave energy dates back to the early 1970s when several research institutes, notably those at Oslo and Trondheim, began investigating novel wave energy conversion systems. A study into the feasibility of building a 200 MW wave power station off Norway's west coast was completed in 1981 and showed that, though feasible, wave energy would be expensive. The generation costs for the four devices studied ranged from 1.2–2.3 Nkr/kWh (11–21 p/kWh). However, subsequent work has shown that small shore-based systems could be considerably more cost-effective and generation costs below 5 p/kWh are expected.

Kvaerner Brug's multiresonant oscillating water column (MOWC)

Site work (heading pic) began at Toftestallen in mid 1984 after extensive model testing and theoretical work, some of which was carried out by the CEGB at Marchwood. The completed chamber measured almost 12 metres square and extended down some 8 metres. Once the base had been prepared the main body of the device (Fig 1) was bolted into place. This consisted of an 11 metre high steel tube open at its base and with a small orifice on top. This part of the programme was completed in October and since then tests have been carried out on air flow through the orifice. Current indications are that the device will produce considerably more power than originally anticipated. However, this will not be fully confirmed until the autumn when the turbine and generator are installed and the system connected to the grid.

A special feature of the design, apart from the use of a Wells turbine, is the use of harbour walls at the base of the device. These form a quarter of wavelength resonator, improving the hydrodynamic performance of the machine and enabling energy to be collected more efficiently over a wider range of sea states.

Norwave's Tapchan

Norwave's tapered channel wave power plant, *Tapchan*, is being built adjacent to the Kvaerner device, making use of a natural inlet in the cliff. The concept is very attractive since it completely eliminates the risk of damage to plant and introduces no new technology. Furthermore, it provides some degree of storage which helps smooth out fluctuations in the output. The lagoon holds sufficient water for 3–4 minutes generation. However, the economics are highly dependent on the careful choice of site so that civil engineering costs are kept to a minimum.

The original plan envisaged anchoring a line of large concrete blocks offshore so as to focus incoming waves onto the ramp. The blocks would act on the waves in the same way as light upon a diffraction grating enabling very much higher water heads to be achieved at the point of foam. This concept has already been proven in tests on models. Theoretical studies indicate that heads of several tens of metres should ultimately be possible in full scale devices. However, this feature has deliberately been omitted from the 350 kW prototype.

Phase-controlled power buoy

A third novel wave energy converter is the phase-controlled power buoy (Fig 5) which was proposed in 1980 by two researchers at the University of Trondheim, Kjell Budal and Johannes Falnes. Like the Kvaerner system, the buoy is also a point absorber, but it works on an entirely different principle.

Official estimates suggest that a 200 MW grid of power buoys could generate electricity at around 1.4 Nkr/kWh (13 p/kWh) although Falnes's own estimates are around half of this figure and he predicts that 3p/kWh may ultimately be achievable with series production **11**.

Government funding has been withdrawn, but Falnes and his team are continuing their work. A one tenth scale model has been tested and was in the sea for 170 days. The buoy has a relatively low investment of energy, materials and money in relation to the energy produced but it is complex and contains a number of critical moving parts.

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